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Star formation time-scales in the nearby, prototype starburst galaxy M82

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ABSTRACT

The last tidal encounter between M82 and M81, some 500 Myr ago, had a major impact on what was probably an otherwise normal, quiescent disc galaxy. It caused a concentrated burst of star formation in the form of massive star clusters, which decreased rapidly, within a few 100 Myr. The current starburst in the centre of the galaxy is likely either due to large-scale propagating star formation or possibly related to late infall of tidally disrupted debris from M82 itself. It may, in fact, be a combination of these two mechanisms, in the sense that the star formation in the active core is actually propagating, while the overall evolution of the starburst is due to tidal debris raining back onto the disc of the galaxy, causing the present-day starburst.

1 M82, THE PROTOTYPE STARBURST GALAXY

M82 is often regarded as the "prototype" starburst galaxy, being the nearest and best-studied example of this class of galaxies. Observations over the entire wavelength range, from radio waves to X-rays (reviewed in Telesco 1988, Rieke et al. 1993), seem indicative of the following scenario. During the last several 100 Myr, tidal interactions with M81, and perhaps also with other galaxies in the same group, induced intense star formation in M82 due to increased gas flows channeled into its centre. The resulting starburst, with the high star formation rate of $\sim 10 M_\odot$ yr^{-1}, has continued for up to about 50 Myr. Energy and gas ejection from supernovae and combined stellar winds drive a large-scale galactic wind along the minor axis of M82 (e.g., Lynds & Sandage 1963, McCarthy et al. 1987, Shopbell & Bland-Hawthorn 1998).

All of the bright radio and infrared sources associated with the active starburst are confined in a small region within a radius of $\sim$ 250 pc from the galaxy's centre; the highest surface brightness regions in the active core, M82 A and C, are indicated in Fig. 1. Most of this volume is heavily obscured by dust at optical wavelengths.

However, there is now ample evidence that the active starburst was not the only major starburst event to have occurred in M82. A region at $\sim 400 - 1000$ pc from the centre, M82 B (Fig. 1), has the high surface brightness and spectral features expected for a fossil starburst with an age $\gtrsim$ 100 Myr and an amplitude similar to the active burst (O'Connell & Mangano 1978, Marcum & O'Connell 1996, de Grijs et al. 2001). Its A-star dominated spectrum is characterised by Balmer absorption lines, and exhibits a large Balmer discontinuity. Emission lines in M82 B are very weak, as opposed to the active starburst, which features intense line emission, in particular of the Balmer lines (Marcum & O'Connell 1996). These are the defining characteristics of the anomalous "E+A" spectra found in distant galaxy clusters, which are generally interpreted as the signature of a truncated burst of star formation that occurred $100 - 1000$ Myr earlier (e.g., Couch & Sharples 1987, Dressler & Gunn 1990, Couch et al. 1998). These starbursts are probably part of the process by which disc galaxies are converted into elliptical or lenticular galaxies and are thought to result from tidal interactions, mergers, or perhaps ram-pressure stripping by the intergalactic medium (Butcher & Oemler 1978, Oemler 1992, Barger et al. 1996).

The significance of the detailed study of M82's starburst environment lies, therefore, in the broader context of galaxy evolution. Starbursts of this scale are likely to be common features of early galaxy evolution, and M82 is the nearest analogue to the intriguing sample of star-forming galaxies recently identified (e.g., the so-called Lyman break galaxies) at high redshifts ($z \gtrsim 3$; Steidel et al. 1996, Giavalisco et al. 1997, Lowenthal et al. 1997). M82 affords a close-up view not only of an active starburst but also, in region B and elsewhere, of the multiple post-burst phases. Other nearby galaxies are known to exhibit one or another of these features, but none of these offers the opportunity to study both at such close range, with a comparably high spatial resolution, or with such a wealth of correlative data, as M82.

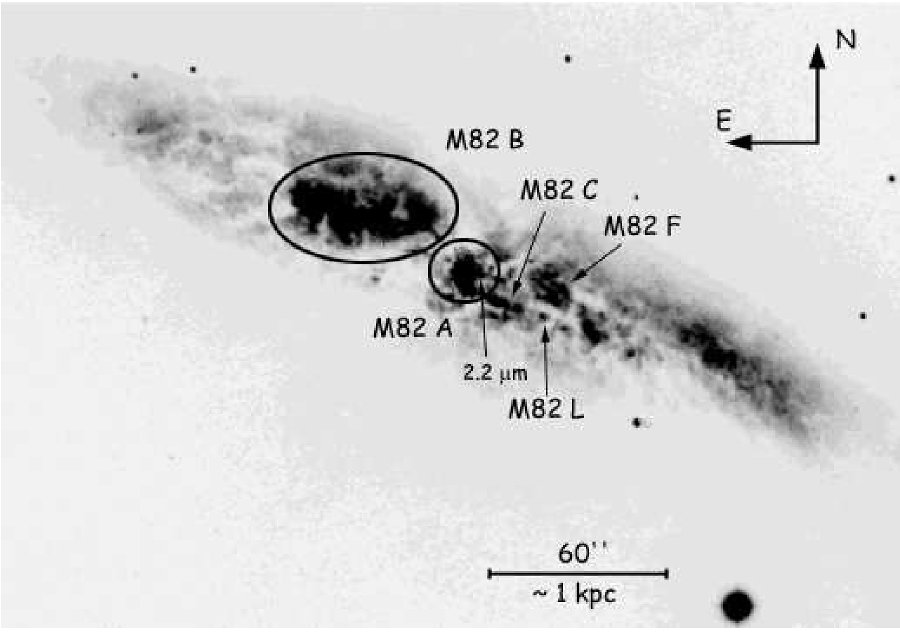

Figure 1. M82 *B*-band image obtained at the Palomar 5m telescope, taken by A. Sandage (exposure time 20 minutes, seeing $\lesssim 1''$). The locations of the active starburst core in M82 A and C, and the older starburst region M82 B are indicated, as well as star clusters F and L. We have also indicated the location of the 2.2 μm peak coincident with the galactic centre; the 390 pc molecular spiral arms studied by Shen & Lo (1995) are located at $15-20''$ on either side of the 2.2μm peak along the galaxy's major axis.

2 TIDALLY-INDUCED STARBURST ACTIVITY – DO THE TIME-SCALES WORK OUT?

Although the M82 starburst regions are pervaded by high-extinction filaments, the outermost parts of the starburst core have lower extinction and can be studied with optical telescopes. However, the use of optical and even near-infrared wavelengths effectively limits our sampling of the M82 starbursts to their surface regions. With this caveat in mind, one can derive the approximate age distribution of the major starburst events in M82 using a variety of tracer objects and methods.

2.1 The Mean Stellar Population in the Disk of M82

Rieke et al. (1993) argued, based on the modelling of integrated, ground-based spectra of the central regions of M82, that the galactic centre has most likely been dominated by two starburst events in the past ~ 30 Myr, spaced by about 25 Myr, each of which had a duration of ~ 5 Myr. Detailed CO observations and Brγ equivalent width measurements (Satyapal et al. 1997) confirm the mean age of the active starburst to be roughly 10 Myr, although this depends to some degree on the detailed time dependence of the star formation rate.

From 20–40 Å resolution ground-based spectrophotometry, Marcum & O'Connell (1996) showed that the spectrum of the active starburst is in fact dominated by a very young, ~ 5 Myr old stellar population, superimposed on an older population with a late-A/early-F star main sequence turn-off and a red-giant clump, corresponding to an age of ~ 600 Myr.

Away from the active centre, in M82 B, the earliest-type stars have evolved off the main sequence, leaving a dominant stellar population with a late-B/early-A star main sequence turn-off, corresponding to an age of ~ 100 Myr (O'Connell & Mangano 1978, Marcum & O'Connell 1996), with possibly an older underlying stellar population.

Using the superb resolution of the Hubble Space Telescope, we were able to resolve the galactic background of M82 B into individual stars for the first time: it is predominantly composed of faint point sources, and these become increasingly dominant at longer (near-infrared) wavelengths, as is clearly illustrated in Fig. 2. Although our magnitude cut-off prevents us from detecting the upper main sequence or giants older than about 80 Myr, a comparison with solar-metallicity Padova isochrones indicates that the brightest M82 giant stars are core helium-burning stars with ages $\sim 20-30$ Myr (de Grijs et al. 2001; Fig. 3). Significant star formation has not occurred in M82 B in the last 10–15 Myr. We based this on a comparison with late-type, young (~ 10 Myr) K and M supergiants in the Large Magellanic Cloud, which are clearly offset from the bulk of the M82 disc stars. Only 4.3% of the integrated near-infrared light originates in the resolved population, implying that the great majority of cool stars were formed at earlier times. For completeness, we mention that the age estimates would not change significantly for metal abundances of $0.4-1.2\times$ solar, the likely range for M82.

2.2 Young Compact Star Clusters

Hubble Space Telescope V and *I*-band imaging of bright optical features in the direction of the core revealed over 100 young compact star clusters (sometimes referred to as "super star clusters") with $M_V \sim -12$, brighter than any star

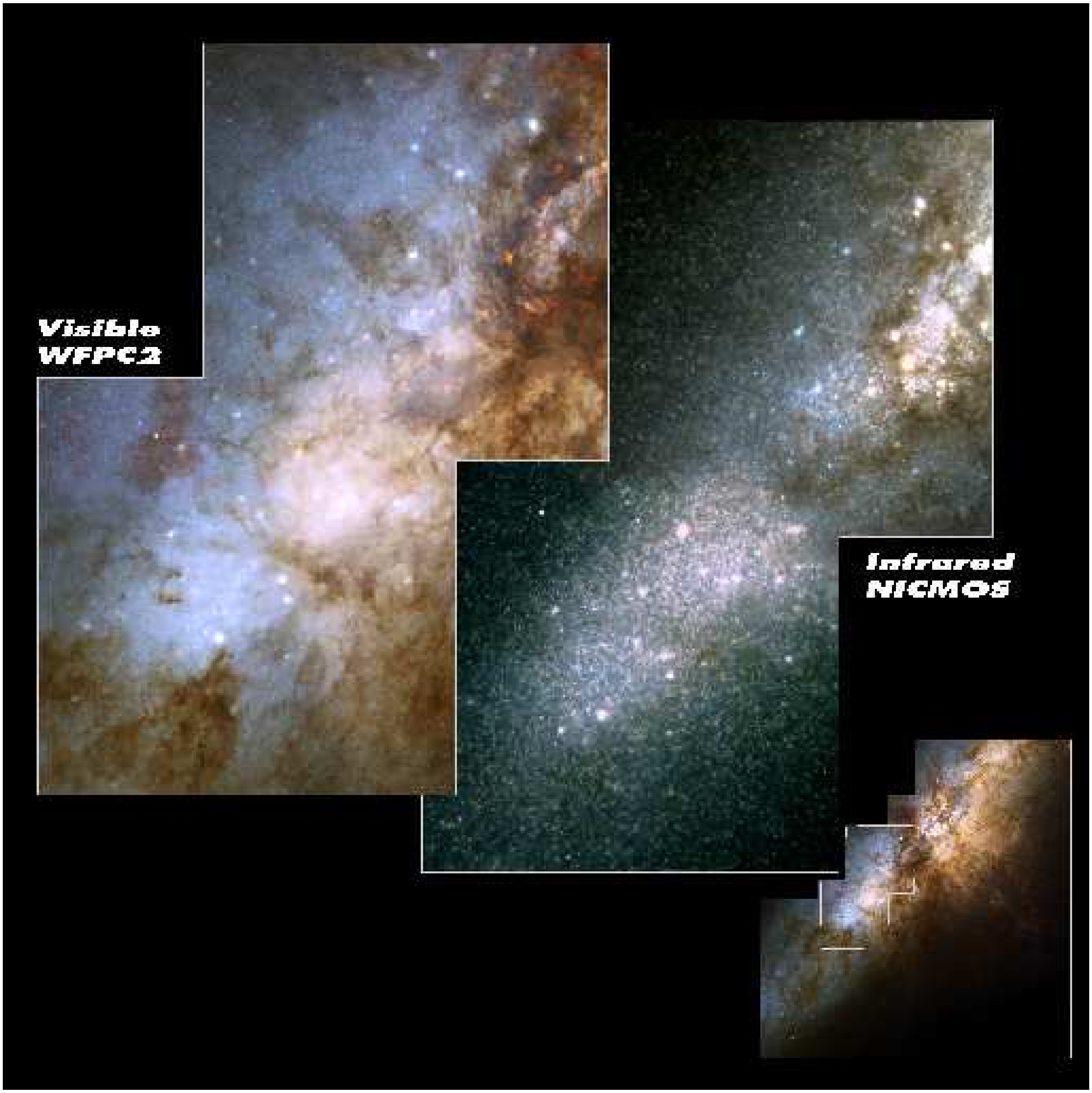

Figure 2. False-colour images of M82 obtained with the *Hubble Space Telescope* in the optical (*WFPC2*) and near-infrared (NICMOS). It is immediately clear that at optical wavelengths the effects of the ubiquitous dust are severe, thus restricting optical studies to the region's surface area. In the near-infrared, large numbers of red giant stars appear, thus allowing us – for the first time – to resolve the disc stellar population in M82. Inset: Full *WFPC2* field of view centred on M82 B. Source: ESA press release, 7 March 2001.

cluster in the Local Group (O'Connell et al. 1995). Ages of these clusters are estimated to be $\sim 10-50$ Myr (O'Connell & Mangano 1978, O'Connell et al. 1995). Satyapal et al. (1997) focused on the highest-luminosity objects in the central starburst at near-infrared wavelengths, assuming that these represent embedded young star clusters deep inside the starburst core. Their best age estimates for these objects, assuming a single formation event, is about 10 Myr, in good agreement with optical age estimates of star clusters and in general agreement with M82's central star formation history.

Two of the bright optical structures near the centre seen on ground-based images deserve further discussion. The brightest star forming region, M82 A (cf. O'Connell & Mangano 1978), corresponds spatially with the conspicuous nuclear peak observed in the near-infrared, at 2.2 μm (see Fig. 1). Ground-based imaging and comparison with stellar population models yields a fairly robust age estimate for

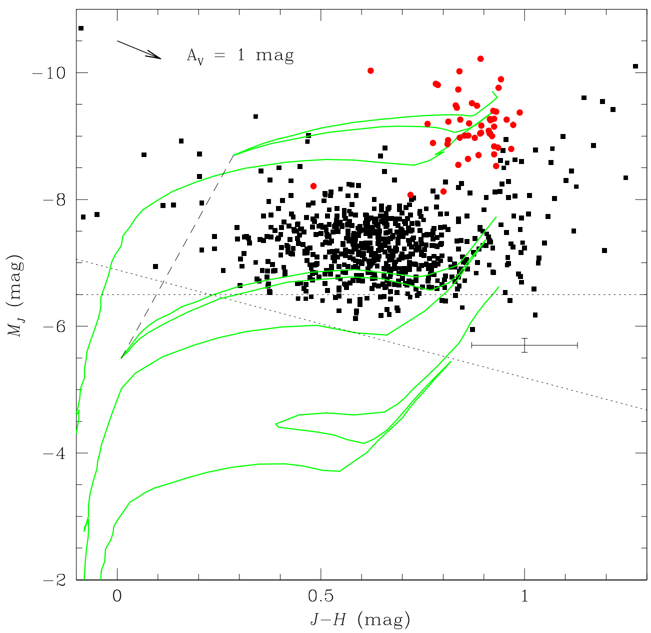

Figure 3. Near-infrared colour-magnitude diagram for the stellar background in the disc of M82. The green lines represent theoretical Padova isochrones for ages of 10, 30, and 100 Myr (top to bottom) and solar metallicity. The dotted lines are the observational selection limits; the dashed lines indicate the envelope of the regions occupied by the theoretical isochrones between 10 and 30 Myr. The scatter in the data points towards the red of the reddest colours reached by the isochrones is most likely due to the effects of dust, as inferred from the direction of the extinction vector. For the same reason, the area close to the blue envelope (dashed line) is underpopulated. Typical observational uncertainties are indicated by the error cross. We have also included K and M supergiants in the Large Magellanic Cloud (red data points). Obviously, field star formation has continued in M82 B until $\sim$ 20 Myr ago. It has evidently been suppressed during the last $\sim 10 - 15$ Myr.

the mean age of M82 A of $\lesssim$ 50 Myr (O'Connell & Mangano 1978, O'Connell et al. 1995). *Hubble Space Telescope* images resolve this star forming knot into more than 50 individual luminous star clusters, superimposed on a bright unresolved background.

Using high-resolution (1.6 Å) ground-based spectroscopy, Gallagher & Smith (1999) recently obtained an age of 60 ± 20 Myr for the very luminous ($M_V \simeq -16$) cluster F, located 440 pc from the galaxy's centre, and a similar age for the nearby, highly reddened cluster M82 L. While M82 F is only a single star cluster, it is very massive ($\sim 1.2 \times 10^6 M_\odot$; Gallagher & Smith 1999, Smith & Gallagher 2001), so its formation would likely have had a noticeable effect on a significant fraction of this extraordinary galaxy: Gallagher & Smith (1999) derive a high local star formation rate, of $> 1 M_\odot$ yr^{-1}, to produce this cluster in a dynamical time of about 1 Myr. However, its high radial velocity with respect to the galaxy's system velocity indicates a highly eccentric orbit (Smith & Gallagher 2001), which must have caused M82 F to travel far from its initial locus in the galaxy. Therefore, we cannot be sure where exactly in M82 this massive star cluster was actually formed.

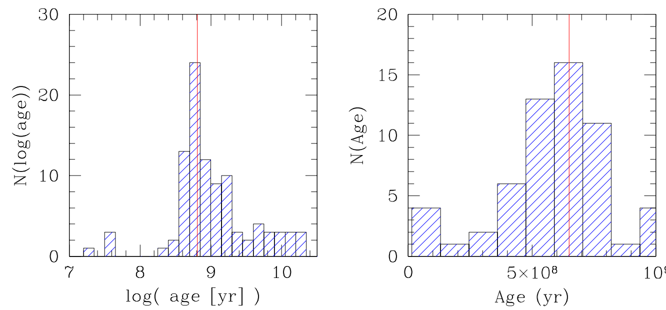

Figure 4. Distribution of compact star cluster ages in M82 B. There is a strong peak of cluster formation at $\sim$ 650 Myr ago (red lines) but very few clusters are younger than 300 Myr. The left-hand panel shows the age distribution of all star clusters on a logarithmic scale; the right-hand panel is a zoomed-in version of the peak cluster formation epoch.

Under the assumption that the older starburst region M82 B is analogous to an evolved and therefore faded version of the active burst in the core, we expected to find a similar, but slightly evolved population of compact star clusters as found in the active starburst core. Indeed, we detected another $\sim$ 110 young compact star clusters in M82 B with intrinsic luminosities of $M_V \gtrsim -9$ (de Grijs et al. 2001), for which we estimated ages from $\sim$ 30 Myr to over 10 Gyr, with a peak near 650 Myr (see Fig. 4), using broad-band optical and near-infrared images (de Grijs et al. 2001). About 22% of the clusters in M82 B are older than 2 Gyr, with a flat distribution to over 10 Gyr. There is a strong peak of cluster formation at $\sim$ 650 Myr ago but very few clusters are younger than 300 Myr (cf. Fig. 4). The full-width of the peak is $\sim$ 500 Myr, but this is surely broadened by the various uncertainties entering the age-dating process. The selection bias of the star clusters in de Grijs et al. (2001) is such that the truncation of cluster formation for ages $<$ 200 Myr is better established than the constant formation rate at ages $>$ 2 Gyr.

Thus, we suggest steady, continuing cluster formation in M82 B at a very modest rate at early times ($>$ 2 Gyr ago) followed by a concentrated formation episode lasting from 400–1000 Myr ago and a subsequent suppression of cluster formation. This leads us to conclude that M82 B has evidently not been affected by the more recent ($<$ 30 Myr) starburst episode now occurring in the central regions.

2.3 Supernova Remnants

The starburst core of M82 is well known to contain a large population of compact supernova remnants (SNRs). These are obscured at optical wavelengths by large amounts of dust, but their structures and evolution have been studied at radio wavelengths (e.g., Kronberg et al. 1985, Huang et al. 1994, Muxlow et al. 1994, Golla et al. 1996, Allen & Kronberg 1998). Based on their sizes and assuming a constant expansion rate, their ages have been estimated at less than a few 100 yr (Huang et al. 1994, Muxlow et al. 1994). Although this does not set tighter constraints on the age of the entire region than spectroscopic age estimates, or age determinations derived from the young star cluster populations, it

confirms our view that the core is significantly younger than regions at larger radii, which are largely devoid of young SNRs or supernovae.

However, even though the starburst core of M82 is pervaded by large amounts of dust, thus making optical studies difficult, one may expect to be able to look into the core itself along certain lines of sight, where there are holes in the dust. It is therefore not unlikely that one would be able to detect the presence of SNRs based on their characteristic ratio of [S II]/Hα line emission.

Hα images, obtained with the *Hubble Space Telescope* as well as ground-based images (e.g., Lynds & Sandage 1963, McCarthy et al. 1987), show that there is relatively little line emission in the disc of M82 at radii larger than 500 pc from the central starburst. The easily visible Hα line emission is concentrated to the core starburst region and the bright minor-axis superwind extending from it.

As mentioned before, despite the high extinction in the starburst core, O'Connell et al. (1995), using optical imaging, found more than 100 young compact star clusters in this area. Since these clusters are most likely of order 10–50 Myr old, it is expected that many heavy stars will already have ended in a supernova explosion. Although some of the roughly 50 radio supernovae and SNRs in M82 (Muxlow et al. 1994, Huang et al. 1994) are expected to be associated with the young star clusters, none appears to coincide with the star clusters seen with the *Hubble Space Telescope* (Golla et al. 1996). A simple, back-of-the-envelope calculation shows that in a population of 100 star clusters of ages similar to those estimated in M82 A and containing between 10^5 and 10^6 stars, one would expect to detect between about 5 and ~ 50 type II SNRs at any given moment, assuming any reasonable range of initial mass functions. The question remains, therefore, why none of the optically-detected young compact star clusters show any evidence for the presence of SNRs.

Golla et al. (1996) suggested that the visible young star clusters in M82 are located in the foreground and outside appreciable concentrations of interstellar gas so that the supernova explosions were unable to sweep up gas and form SNRs. However, this does not explain why we do not see any SNRs associated with the visible star clusters. It would also imply that 1500–3000 young star clusters exist in the core of the galaxy, which seems an unrealistically high number. Therefore, they suggest that the detected radio supernovae and SNRs are hidden behind dense layers of dust so that the associated star clusters are not seen.

This argument has apparently gained support from recent observations of HI absorption towards many radio supernovae and SNRs in M82 (Wills et al. 1998), the amount of which seemed to imply that all radio-detected sources in M82 are hidden behind an impenetrable layer of dust (estimated mean extinction $\langle A_V \rangle = 24 \pm 9 mag$; Mattila & Meikle 2001). However, this assumes that all objects detected at radio wavelengths are associated with, or are hidden behind, dense molecular clouds, which does not seem plausible: O'Connell et al. (1995) point out that the geometrical arrangement of the young compact star clusters resembles the structure of the starburst so that at least some of the observed clusters are located far inside M82. In fact, they derived a mean extinction towards M82 A of about 3 magnitudes, while Satyapal et al. (1997) argue that the 12 most luminous compact near-infrared sources are deeply embedded star clusters in the starburst core, thus also implying optical depths < 1 at near-infrared (K band) wavelengths along these sight lines. In addition, the extinction measured toward M82 F is only about 5 magnitudes although the cluster is located far inside M82 (Gallagher & Smith 1999).

Therefore, we suggest instead that the conditions in and near young star clusters may be particularly hostile at least for the formation of SNRs (Greve et al. 2001), i.e., the matter ejected by supernovae is quickly dispersed because of stellar winds, nearby supernova explosions, and the strong gravitational field of the star clusters. In addition, the interstellar medium in these clusters is possibly dense (Huang et al 1994), thus limiting SNRs to very small sizes (Huang et al. 1994, Muxlow et al. 1994). It is therefore possible that in and near young star clusters there are only a few short-lived radio supernovae but no, or very few, and small, SNRs.

Although we do not expect to detect SNRs in the older starburst region, M82 B, simply because of its estimated mean age of a few 100 Myr, we do detect diffuse Hα emission, but at much lower levels than in the active starburst and in the bright superwind (de Grijs et al. 2000).

Clearly, many of the optically detected compact star clusters (de Grijs et al. 2001) have little or no Hα emission, which is not unexpected if these clusters are indeed older than a few 100 Myr. However, some compact Hα emission regions have inconspicuous continuum counterparts. In addition, there seems to be a gradient in Hα emission within M82 B: there are few compact Hα sources far away from the central starburst, whereas both compact sources and diffuse emission are seen nearer to the starburst core, although still at a surface brightness $20\times$ lower than in the active starburst.

One expects to find two types of compact Hα sources in a galaxy like M82. H II regions will exist around young star clusters with ages $\lesssim 10$ Myr because of the presence of ionizing O- or early B-type stars. Even for very young H II regions, including those that suffer from significant extinction, there should always be a significant continuum source associated with these. Alternatively, Type II supernovae can also produce compact Hα remnants. These will often be associated with their parent star clusters, but in many cases there may be no well-defined compact continuum source. Since Type II supernovae can occur up to 50 Myr after a star formation event, the associated cluster may have faded due to evolutionary effects or dynamically expanded enough to be inconspicuous against the bright background of the galaxy. Alternatively, the parent star of the SNR could have been ejected from the cluster or could have formed initially in the lower density field stellar population. In fact, studies of resolved starbursts suggest that 80–90% of the bright stellar population resides in a diffuse component outside of compact clusters (e.g., Meurer et al. 1995, O'Connell et al. 1995), which is partially replenished by the dissolution of star clusters on time-scales of ~ 10 Myr (cf. Tremonti et al. 2001).

We presented acceptable evidence that the 10 most luminous compact Hα sources in M82 B could be SNRs (de Grijs et al. 2000). Six of these have only faint counterparts in the continuum passbands and some of the sources show evidence of limb brightening, as might be expected for older SNRs. Their Hα luminosities, surface brightnesses and sizes

are consistent with those of SNRs in other star-forming galaxies. However, none of these Hα-bright SNR candidates, with one possible exception, appear to show 8.4 GHz radio emission brighter than our detection limit associated with them. However, most of the bright 8.4 GHz sources are located in areas with higher than average extinction, where detection of optical continuum or Hα counterparts would be difficult.

It is not unusual for SNRs to be Hα bright while lacking significant emission at radio wavelengths. Radio and Hα emission are due to different physical processes and are prominent at different evolutionary stages of the SNR; radio emission arises earlier in SNR evolution than Hα emission.

The presence of SNRs in M82 B can help to set limits on its star formation history. The last supernovae in a quenched starburst would occur at a time comparable to the longest lifetime of a supernova progenitor after the end of the starburst activity. The time spent between the zero-age main sequence and planetary nebula phase by an $8M_\odot$ progenitor star, which is generally adopted as a lower limit for Type II supernovae (e.g., Kennicutt 1984), corresponds to $\sim 35-55$ Myr (Iben & Laughlin 1989, Hansen & Kawaler 1994). Type Ia supernovae, which involve lower mass stars in binary systems, can occur much later, but one expects these to be more uniformly distributed over the galaxy's surface, not concentrated near regions of recent star formation.

Therefore, if our candidates are indeed SNRs they suggest an upper limit to the end of the starburst event in M82 B closest to the active starburst core of ~ 50 Myr. The evidence that these objects are actually SNRs is only circumstantial, however. Although their properties seem to compare better to SNR samples in other galaxies than to those of HII regions, they could be HII regions which have been affected by the unusual physical circumstances in M82's disc. A straightforward test would be to obtain [S II]/Hα emission line ratios for these sources, since these are sensitive to the presence of strong shock waves.

3 THE OVERALL STAR FORMATION HISTORY OF M82

These results suggest that starburst activity in M82 is of longer duration than had been supposed and has possibly propagated through the galaxy's disc (Shen & Lo 1995, Satyapal et al. 1997, de Grijs et al. 2000). Combining the wealth of observational information for the M82 starbursts, the following picture for its star formation history emerges.

The observed distribution of gas in the M81/M82 group of galaxies is consistent with a 3-body model, including M81, M82 and NGC 3077, in which there was a close passage between M82 and M81 (at a distance of 21 kpc), which started ~ 500 Myr ago (Brouillet et al. 1991), and lasted for some 300 Myr (Yun 1999). This independent dynamical estimate of the last M81/M82 passage is remarkably close to the peak of the cluster formation burst in M82 B.

We suggest therefore, that the last tidal encounter between M82 and M81 had a major impact on what was probably an otherwise normal, quiescent disc galaxy. It caused a concentrated burst of star formation, as evidenced by the peak in the age distribution of the cluster sample in M82 B. Comparison of the cluster ages with the integrated light dating in this region ($\sim 100-200$ Myr) suggests that field star formation may have continued at a high rate after cluster formation had begun to decline, but the uncertainties in the methods are large. The enhanced cluster formation decreased rapidly within a few hundred Myr of its peak. However, field star formation continued in M82 B, although probably at a much lower rate, until ~ 20 Myr ago. It has evidently been suppressed during the last $\sim 10-15$ Myr, during which the starburst in the core of M82 has been most active. Evidence for supernova remnants in the parts of M82 B nearest the starburst core indicates that disc star formation during the last 50 Myr was more active nearer the nucleus.

At intermediate radii, between the active core and M82 B, Shen & Lo (1995) presented evidence for a change in the velocity dispersion properties of the interstellar medium: they suggest that the much higher velocity dispersion of the CO gas in the molecular spiral arms at ~ 390 pc from the core compared to the gas in the inner spiral arm at 125 pc indicates that the outer gas was disrupted by an earlier starburst. Although we cannot rule out the possibility that the starburst may in fact have propagated inwards towards M82's core, this view is also consistent with the dual-starburst hypothesis of Rieke et al. (1993), suggesting that the 30 Myr starburst occurred in the outer spiral arm and the more recent ~ 5 Myr-old starburst in the inner arms, which happened sufficiently recently for the interstellar medium to remain relatively undisturbed.

Satyapal et al. (1997) presented a wealth of observational information probing the central 500 pc, from which they concluded that there is a significant age dispersion among the compact luminous infrared sources (i.e., the embedded star clusters) within the central starburst, of about 6 Myr. Most interestingly, the age dispersion appears to be correlated with projected distance from the core, leading these authors to argue that the central starburst is possibly propagating outwards towards the western edge of the starburst core, i.e., as a continuation of the proposed propagation direction inferred from the overall starburst geometry in M82.

Independent HI observations with MERLIN and the VLA (Pedlar & Wills, priv. comm.) suggest a similar scenario: the compact sources which correspond to young radio SNRs (whose progenitors have ages of ~ 10 Myr), are much more extended throughout the central 750 pc of the disc of M82 than the younger, ~ 1 Myr-old objects identified as HII regions. These latter sources are found to be mostly concentrated towards the western edge of the galactic centre, in the same sense as the star formation propagation direction proposed by Satyapal et al. (1997).

Thus, the current starburst in the centre of the galaxy is either due to large-scale propagating star formation throughout the disc of the galaxy or possibly related to late infall of tidally disrupted debris from M82 itself, caused by dynamical feedback due to its gravitational potential (O'Connell & Mangano 1978, Yun et al. 1993). It may, in fact, be a combination of these two mechanisms, in the sense that the star formation in the active core is actually propagating (cf. Satyapal et al. 1997), while – as we suggested (de Grijs et al. 2001) – the overall starburst scenario is one in which the last tidal interaction caused intense star formation in M82

B, of which the ejecta have recently rained back onto the disc, causing the present-day starburst.

Finally, a strong tidal interaction could easily produce an off-nuclear starburst at a site like M82 B, although the M82 B burst could also have been part of a larger scale event encompassing the centre of the galaxy as well. Given the high extinction and the dominance by much younger concentrations of stars, it would not be easy to identify older clusters in the starburst core, if they exist. At the distance from the centre of region B, one would expect M82's differential rotation (cf. Shen & Lo 1995) to have caused the starburst area to disperse on these time-scales. The reason why the fossil starburst region has remained relatively well constrained is likely found in the complex structure of the disc. It is well-known that the inner ~ 1 kpc of M82 is dominated by a stellar bar (e.g., Wills et al. 2000) in solid-body rotation. From observations in other galaxies, it appears to be a common feature that central bars are often surrounded by a ring-like structure. If this is also true for M82, it is reasonable to assume that stars in the ring are trapped, and therefore cannot move very much in radius because of dynamical resonance effects. The phase mixing around the ring might be slow enough for a specific part of the ring to keep its identity over a sufficient time so as to appear like region B (Gallagher, priv. comm.): if the diffusion velocity around the ring is sufficiently small, any specific region would remain self-constrained for several rotation periods. In addition, since the density in the region is high, simple calculations imply that the area's self-gravity is non-negligible compared to the rotational shear, therefore also prohibiting a rapid dispersion of the fossil starburst region.

4 THE NATURE OF THE YOUNG COMPACT STAR CLUSTERS IN M82 B

The evidence for decoupling between cluster and field star formation is consistent with the view that young star cluster formation requires special conditions, e.g., large-scale gas flows, in addition to the presence of dense gas (cf. Ashman & Zepf 1992, Elmegreen & Efremov 1997).

Production of luminous, compact star clusters such as those described above seems to be a hallmark of intense star formation episodes. They have been identified in several dozen galaxies, often involved in interactions (e.g., Holtzman et al. 1992, Whitmore et al. 1993, O'Connell et al. 1994, Conti et al. 1996, Watson et al. 1996, Carlson et al. 1998, de Grijs et al. 2001). Their sizes, luminosities, and – in several cases – masses are entirely consistent with what is expected for young globular clusters (Meurer 1995, van den Bergh 1995, Ho & Filippenko 1996a,b, Ho 1997, Schweizer & Seitzer 1998, de Grijs et al. 2001).

It is possible that a large fraction of the star formation in starbursts takes place in the form of such concentrated clusters. The discovery that globular cluster formation, once thought to occur only during early stages of galaxy evolution, continues today is one of the Hubble Space Telescope's main contributions to astrophysics to date.

Young compact star clusters are therefore important because of what they can tell us about globular cluster formation and evolution (e.g., destruction mechanisms and efficiencies). They are also important as probes of the history of star formation, chemical evolution, initial mass function, and other physical characteristics in starbursts. This is so because each cluster approximates a coeval, single-metallicity, simple stellar population. Such systems are the simplest to model, and their ages and metallicities and, in some cases, initial mass functions can be estimated from their integrated spectra.

Using the individual age estimates obtained for the star clusters in M82 B, we can now apply the age-dependent mass-to-light ratio predicted for a theoretical single burst stellar population to derive estimated masses for this cluster sample. Assuming a "standard" Salpeter (1955) initial mass function, we find that the masses of the young clusters in M82 B with $V \leq 22.5$ mag are mostly in the range $10^4 - 10^6 M_\odot$, with a median of $10^5 M_\odot$.

The high end of the M82 B cluster mass function overlaps with those estimated by similar techniques for young compact star clusters in other galaxies (e.g., Richer et al. 1993, Holtzman et al. 1996, Tacconi-Garman et al. 1996, Watson et al. 1996, Carlson et al. 1998). Independent dynamical mass estimates are available only for a few of the most luminous young star clusters, including M82 F, NGC 1569A and NGC 1705-1, and are approximately $10^6 M_\odot$ (Ho & Filippenko 1996a,b, Smith & Gallagher 2001). Because of the proximity of M82, we have been able to probe the young cluster population in M82 B to fainter absolute magnitudes, and thus lower masses, than has been possible before in other galaxies. Other young star cluster samples are biased toward high masses by selection effects.

The M82 B cluster masses are comparable to the masses of Galactic globular clusters (e.g., Mandushev et al. 1991, Pryor & Meylan 1993), which are typically in the range $10^4 - 3x10^6 M_\odot$. Some of the clusters show evidence for asymmetries or subclustering, possibly an indication of either mergers or extreme youth, implying that these objects have not yet reached virial equilibrium. The M82 B cluster sizes are consistent with values found for the young compact star cluster populations in the starburst core in M82 and other galaxies and with the progenitors of globular clusters.

If these clusters survive to ages of $\gtrsim 10$ Gyr, the M82 B clusters will have properties similar to those of disc population Galactic globulars. However, the young globular cluster scenario would be considerably strengthened if we could measure their masses directly. Recently, Smith & Gallagher (2001) presented convincing evidence that M82 F is likely dominated by a "top-heavy" present-day mass function, truncated at $2 - 3 M_\odot$. However, such claims, e.g., Rieke et al.'s (1993) result for the main disc population in M82, have often turned out to be erroneous in retrospect (see the review by Scalo 1998). While variations in the initial mass function do occur, they occur mostly on the scales of individual star forming regions, while the large-scale initial mass function remains largely constant (e.g., Kroupa 2001). Smith & Gallagher (2001) therefore caution that M82 F, and also the massive young star cluster NGC 1705-1, may indeed be an intermediate and high-mass anomaly, possibly caused by mass segregation effects at birth, in an otherwise "normal" larger-scale star forming complex. Either way, the implication of such a localised variation in the present-day (or initial) mass function would clearly be that such objects will not survive to become old Galactic globular cluster analogues, simply because they lack long-lived low-mass stars.

It is therefore expected that they will dissolve within a few Gyr of their formation.

Thus, although all integrated observational properties of these young star clusters point towards a Galactic globular cluster-like evolution, only high-dispersion spectroscopy will allow us to assess their present-day (or perhaps their initial) mass function shape, and hence their survival chances to become old Galactic globular cluster analogues.

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